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Igor Krupnik, Michael A. Lang,
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Editors

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Southern Ocean Primary Productivity: Variability and a View to the Future

Walker O. Smith Jr. and Josefino C. Comiso

ABSTRACT. The primary productivity of the Southern Ocean south of 58°S is assessed using satellite data on ice concentrations, sea surface temperatures, and pigment concentrations, a vertically generalized production model, and modeled photosynthetically active radiation. Daily productivity is integrated by month and by year to provide an estimate of new production. The productivity of the Southern Ocean is extremely low relative to other oceanic regions, with annual net rates throughout the region of less than 10 g C m^{-2}. This low annual value is largely the result of negligible productivity throughout much of the year due to low irradiance and high ice cover. Despite the annual oligotrophic state, monthly productivity during the summer (December through February) is substantially greater, averaging from 100 to 1,500 mg C m^{-2} mo^{-1}. Substantial interannual variability occurs, and certain subregions within the Southern Ocean experience greater interannual variations than others. Those regions, like the West Antarctic Peninsula, the Ross Sea polynya region, and the Weddell Sea, are characterized as being continental shelf regions and/or those that are substantially impacted by ice. Despite this relationship, no significant changes in primary production were observed in regions where large trends in ice concentrations have been noted. The driving forces for this variability as well as the implications for long-term changes in regional and Southern Ocean productivity are discussed.

INTRODUCTION

The Southern Ocean is a vast region within the world's oceans that has presented some significant challenges to oceanographers. It is the site of large numbers of birds, marine mammals, and fishes and extensive sedimentary deposits of biogenic material, and is presently being impacted by physical forcing external to the region, such as ozone depletion (Neale et al., 1998, 2009, this volume) and climate change (e.g., Vaughan et al., 2003). However, because of its size and remoteness, it is difficult to conduct experimental programs to adequately assess the role of various environmental factors on biological processes in the region. In addition, a large fraction of the Southern Ocean is ice covered for much of the year, restricting access to many locations and making sampling of other regions nearly impossible. To assess the productivity of the entire Southern Ocean, it is necessary to "sample" using techniques that can quantify processes over large

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spatial scales through time. At present, the only means to accomplish this on the appropriate scales is via satellite oceanography.

Satellites presently have the capability to accurately map the distributions of ice (Comiso, 2004), sea surface temperature (SST; Comiso, 2000; Kwok and Comiso, 2002), and pigment concentrations (Moore and Abbott, 2000), as well as other parameters such as winds, bathymetry, cloud cover, and some gas concentrations such as ozone (Comiso, 2009). Some measurements use visible wavelengths and reflectance from the surface, and therefore the data returned are reduced in space and time because of clouds; others are either passively detected or use other wavelengths to determine the distribution of the variable. In biological oceanography a major variable of interest is ocean color, which is converted into quantitative estimates of pigment (chlorophyll) concentrations. While the estimates include significant error terms (because of the dependence of pigment estimates as a function of latitude, the limitation of reflectance to the optical surface layer rather than the entire euphotic zone, and the interference in some waters of dissolved organic matter), these estimates remain, and will remain, the only means to obtain synoptic assessments of phytoplankton distributions over large areas as well as their temporal changes over relatively short (e.g., days) periods.

Two satellites have provided nearly all of the data in the past three decades on pigment distributions in the Southern Ocean. The first was the Nimbus 7 satellite, launched in 1978, which carried the Coastal Zone Color Scanner (CZCS). While questions concerning the data quality and coverage from CZCS have been voiced, the data were used to investigate both the large-scale distributions of pigments in relation to oceanographic variables (Sullivan et al., 1993; Comiso et al., 1993) and also the specific processes and regions (e.g., Arrigo and McClain, 1994). However, given the orbit, the frequency of data collection in the Southern Ocean was quite restricted, and when compounded by the loss of data from cloud cover, the temporal frequency was far from optimal. In 1996 the ORBView-2 satellite was launched, which included the Sea-viewing Wide Field-of-view Sensor (SeaWiFS). This satellite proved to be an extremely useful tool for biological oceanographers, as the sampling frequency was much greater and the data return in polar regions was far greater. For example, Moore et al. (1999) were able to detect a short-lived bloom in the Pacific sector of the Southern Ocean that was only infrequently sampled by ships. Dierssen et al. (2002) assessed the variability of productivity in the West Antarctic Peninsula region and found (based on a model) that pigment concentrations were the dominant variable creating variations in space and time. Smith and Comiso (2008) assessed the productivity of the entire Southern Ocean and found that the "hot spots" of production were limited to continental shelf regions, and suggested that this was a result of low iron concentrations coupled with deeper mixing in the offshore regions. The interaction of low iron and low irradiance (Sunda and Huntsman, 1997; Boyd and Abraham, 2001) gives rise to a large spatial limitation over broad areas.

It is the purpose of this manuscript to look at the scales of variability in the Southern Ocean as a whole and to determine where such variations are large by using primary production derived from SeaWiFS ocean color and advanced very high resolution radiometer (AVHRR) SST data in conjunction with a bio-optical model. We also will compare the modeled productivity with observed values, where those data are available to test the robustness of the model. Finally, some aspects of the temporal patterns of productivity in the Southern Ocean are reviewed.

MATERIALS AND METHODS

Primary productivity was estimated using various data derived from satellites and a bio-optical model. The model was a vertically generalized production model (Behrenfeld and Falkowski, 1997b), in which primary productivity (PP_{eu}, in units of mg C m^{-2} d^{-1}) was estimated from the following equation:

$$PP_{eu} = 0.66125 \times P^B_{opt} \frac{E_o}{E_o + 4.1} C_{Sat} \times Z_{eu} \times D_{Irr}$$

where P^B_{opt} is the optimal rate of photosynthesis within the water column (mg C (mg chl)$^{-1}$ h^{-1}) and is a function of temperature, E_o is the surface daily photosynthetically active radiation (PAR, mol photons m^{-2} d^{-1}), C_{sat} is the surface chlorophyll concentration (mg chl m^{-3}) determined by satellite, Z_{eu} is the depth of the euphotic zone (m), and D_{Irr} is the photoperiod (h). P^B_{opt} was estimated from sea surface temperatures by the polynomial equation of Behrenfeld and Falkowski (1997b), and all P^B_{opt} values at temperatures less than -1.0°C were set to 1.13.

Temperature, PAR, ice concentrations, and chlorophyll concentrations were derived from different satellite data sets. Different satellite data were mapped to the same grid as described below. We arbitrarily defined the Southern Ocean roughly as the region impacted by seasonal ice movements and hence set the northern boundary at 58ºS. Ice concentrations and associated parameters (e.g., ice extent and area) were derived using data from the Special Sensor Microwave Imager (SSM/I) on the Defense Meteorological Satellite Program and mapped on a polar stereographic grid at a 25 × 25 km resolution. Ice concentrations were derived from satellite passive microwave data using the enhanced bootstrap algorithm used for Advanced Microwave Scanning Radiometer-EOS data and adapted for SSM/I data (e.g., Comiso et al., 2003; Comiso, 2004). Sea surface temperatures were derived from thermal infrared channels of the NOAA AVHRR as described in Comiso (2003). Pigment concentrations derived from SeaWiFS data were provided by the NASA Goddard Earth Sciences Distributed Active Archive Center. Surface temperature and pigment concentration data have been gridded in the same manner as the sea ice concentration data but on a 6.25 × 6.25 km resolution. Mean daily pigment concentrations were estimated using the standard SeaWiFS algorithm with OC4 (Version 4) calibration (Patt et al., 2003) and used to generate weekly (seven-day bins) and monthly data sets from 1997 to 2006. Photosynthetically active radiation data were extracted as part of the SeaWiFS data but were not used in the estimates of productivity because a large fraction of the valuable polar data was inadvertently masked as ice covered by the SeaWiFS data processing group. We used a modeled PAR instead (which provided basically the same results) for much improved coverage. It is important to recognize that because of cloud and ice masking the weekly and monthly averages do not reflect true averages but are averages of daylight data (for each data element) available during clear-sky, ice-free conditions only.

Productivity was calculated on a daily basis and binned in a manner similar to that of chlorophyll. The gridding technique (Smith and Comiso, 2008) and the presence of clouds caused a large fraction of data elements (pixels) in the daily maps to have missing data. In the case where an empty pixel is surrounded by pixels with data, a simple interpolation technique is utilized to estimate the pigment level in the empty pixel. For larger data gaps, a combination of spatial and temporal interpolation was utilized. Such interpolation filled only a very small fraction of missing data in the daily maps, and for time series studies, weekly averages were produced as the basic product. In a similar manner, annual productivity was estimated by summing weekly averages over an entire year. Standard deviations were calculated for all pixels, but because of the variable number of data points within each pixel, we arbitrarily used only those locations where at least five means were available to calculate variations.

We recognize that regional algorithms have been developed for certain parts of the Southern Ocean (e.g., Ross Sea: Arrigo et al., 1998; Dierssen and Smith, 2000) and that these formulations provide a more accurate estimate of phytoplankton biomass in each area. We chose to use the output from the standard global algorithm to simplify the comparison of regions and of various years, to facilitate a comparison among all regions, and to avoid problems of defining boundaries of optically different regions. While this approach may introduce error into absolute estimates of productivity within a region, it provides a uniform basis to compute productivity throughout the Southern Ocean, as regional algorithms (some of which need more rigorous validation) are not available for all areas.

RESULTS

SPATIAL MEANS AND VARIABILITY

Annual productivity of the Southern Ocean is highly variable but also quite low relative to other oceans, as has been suggested based on discrete measurements (e.g., Smith and Nelson, 1986; Nelson et al., 1996; Tremblay and Smith, 2007). Much of the region off the continental shelf is oligotrophic and is characterized by primary production rates of less than 50 g C m^{-1} y^{-1} (Figure 1). Regions of

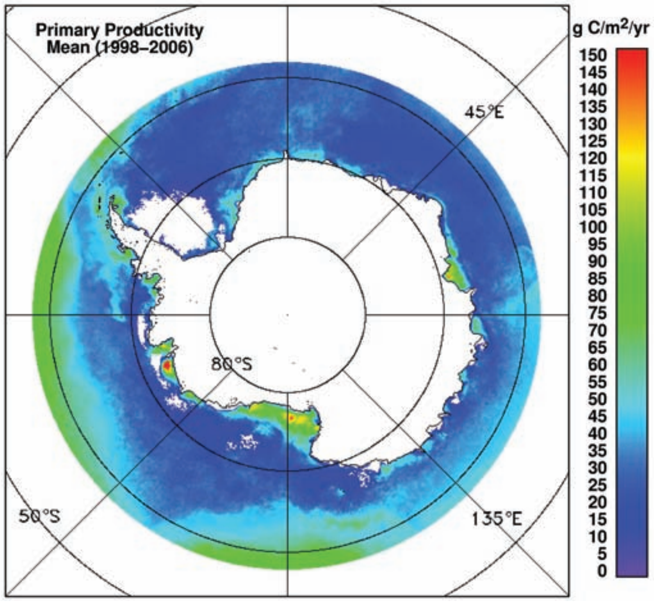

FIGURE 1. Mean (1998–2006) modeled productivity of the Southern Ocean as derived from a vertically integrated productivity model.

enhanced (threefold greater than the low-productivity offshore areas) do occur on the continental shelf, with three areas being noteworthy: the Ross Sea, the Amundsen Sea, and Prydz Bay/East Antarctic shelf. Productivity in the Ross Sea is spatially extensive, but the greatest absolute productivity is in the Amundsen Sea region (150 g C m^{-1} y^{-1} at ~73°S, 110°W). It is interesting that this particular region has never been sampled because of the difficulty of gaining access by ships.

Productivity in the more northern regions (near the location of the Antarctic Circumpolar Current (ACC) and its associated fronts, e.g., Abbott et al., 2000) is elevated in the Pacific sector (between 45° and 135°W) and south of New Zealand (between 155°W and 165°E), averaging ~75 g C m^{-1} y^{-1}, and can be contrasted with the very low productivity waters of the South Atlantic and Indian Ocean sectors (Figure 1). Productivity of the South Atlantic is greater farther north than that in our selected study region (58°S; Moore and Abbott, 2000; Smith and Comiso, 2008), and the region we analyzed is also largely south of the ACC (Moore and Abbott, 2000) and largely free of frontal enhancements. The Indian Ocean sector is among the windiest areas on Earth, and hence deep mixing would be expected to occur. Regardless, the annual productivity in the southern Indian Ocean and South Atlantic areas is less than 20 g C m^{-1} y^{-1}, among the lowest anywhere in the world's oceans.

Computed standard deviations for the entire Southern Ocean suggest that while the absolute variations occur in the most productive continental shelf regions such as the Ross Sea, the relative spatial variations are actually greater elsewhere (Figure 2). For example, in the Ross Sea the standard deviation expressed as a percentage of the mean is only 2.8%, whereas in the southern Weddell Sea they range from 5.4% to 20%, suggesting the spatial variability in that location is much greater. This likely is due to the impact of ice, which varies greatly in this location interannually (Smith and Comiso, 2008). The highest productivity occurs in areas of polynyas; in the Ross Sea the standard deviation is not as large because the location of the polynya is basically the same from one year to another. Variations in the Amundsen Sea, the location of the productivity maximum, are also less than in other regions, being similar to those in the Ross Sea (~1.5%–3%). Variations in the South Atlantic can be substantial (~10% near the location of the Weddell Sea polynya and Maud Rise) as well. Conversely, the elevated productivity region in the Pacific sector north of 62°S exhibits quite low variability (generally less than 1%).

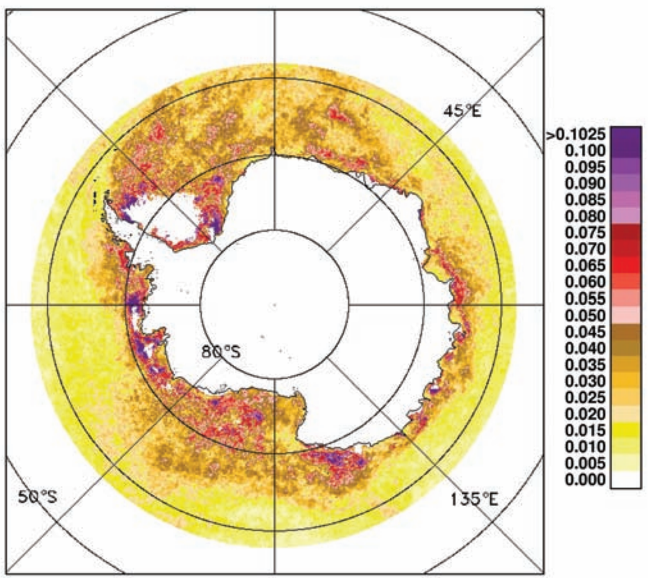

FIGURE 2. Standard deviation of the derived annual productivity values. Only those pixels where there were at least five years of data (from 1998 to 2006) were included. Black regions are those with fewer than five values; white areas have no data.

SEASONAL PRODUCTIVITY AND VARIABILITY ON MONTHLY SCALES

The broad seasonal progression of productivity in some regions of the Antarctic is relatively well known. For example, in the Ross Sea a rapid increase in phytoplankton biomass and productivity occurs in spring, and a decline begins in mid-December to early January. Much of the summer is characterized by relatively low biomass and productivity (Smith et al., 2000, 2003). Productivity in the West Antarctic Peninsula region also is characterized by a similar pattern (Ducklow et al., 2006), although the magnitude of the productivity is far less (Smith and Comiso, 2008). December productivity in the Southern Ocean parallels the annual pattern, with the maximum productivity occurring in the Amundsen and Ross seas and East Antarctic continental shelf (Figure 3). Clearly, the high-productivity areas are those of the continental shelf. Productivity north of 62°S is also higher in the Pacific sector. January productivity is characterized by increased rates and spatial extents in the Amundsen and Weddell seas, as well as at the tip of the Antarctic Peninsula, but by a decrease in the Ross Sea. February rates show a general decrease, with decreases being most noticeable in the East Antarctic region, the peninsula area, Amundsen Sea, and

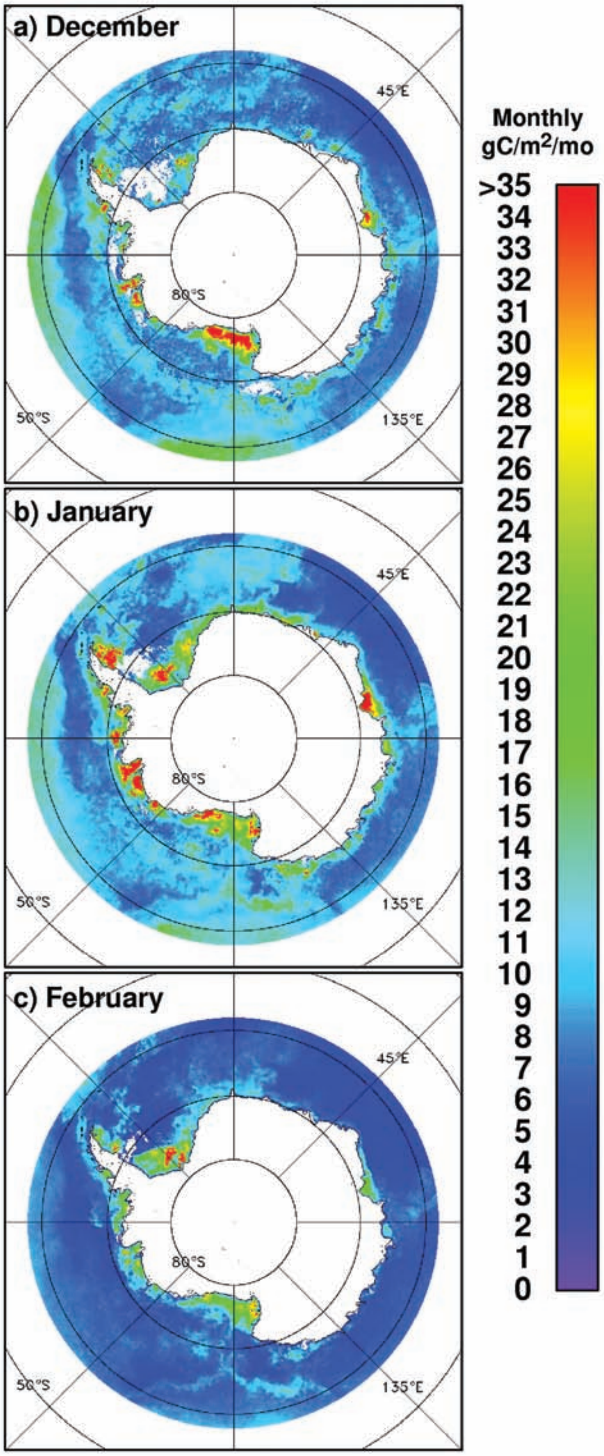

FIGURE 3. Mean monthly productivity of the Southern Ocean for the years 1998–2006 for (a) December, (b) January, and (c) February.

the Pacific sector north of 62°S. All sites show the generalized maximum in late spring or early summer, followed by a decrease, although the timing of various sites varies.

Variability on a monthly basis appears to be larger than on an annual basis (Figure 4). For example, relative variations in the Ross Sea are ~7% in all months, suggesting that the annual variations are somewhat dampened by the effects of long low-productivity periods. December variations are difficult to assess, as many locations have fewer than five years of data and hence no standard deviation was calculated. However, variability in general seems to increase slightly in February, which may reflect the relatively stochastic occurrence of storms (and hence deep mixing) during that period.

DISCUSSION

Primary productivity estimates in the Southern Ocean have been made for decades but have resulted in a biased picture of photosynthesis and growth. This is largely because historically, estimates have been made in ice-free waters (e.g., Holm-Hansen et al., 1977; El-Sayed et al., 1983), whereas polynyas, which are known to be sites of intensive productivity (Tremblay and Smith, 2007), have rarely been sampled. Additionally, open water regions of low production have largely been ignored, and sampling has concentrated on the high-productivity locations thought to support local food webs. The richness of upper trophic levels that has been observed for over 100 years (e.g., Knox, 1994) was so marked that it was assumed that primary production must occur to support this abundance. However, we now recognize that productivity in the Southern Ocean is not great (Smith and Nelson, 1986), particularly on an annual basis, and the abundant higher trophic level standing stocks and extensive biogenic sedimentary deposits are forced by food web efficiency, alternate food sources, and uncoupling of carbon with silica in biogeochemical cycles (Nelson et al., 1996).

With the advent of satellite oceanography, large, synoptic measurements of phytoplankton biomass became available. Such estimates in the Southern Ocean were far less common than in tropical and temperate waters, but they were very useful in showing the relationship of chlorophyll with ice distributions (Nelson et al., 1987; Sullivan et al., 1993), hydrographic features and fronts (Moore and Abbott, 2000), and depth (Comiso et al., 1993). In general, early satellite studies suggested that coastal zones and marginal ice zones were sites of large phytoplankton

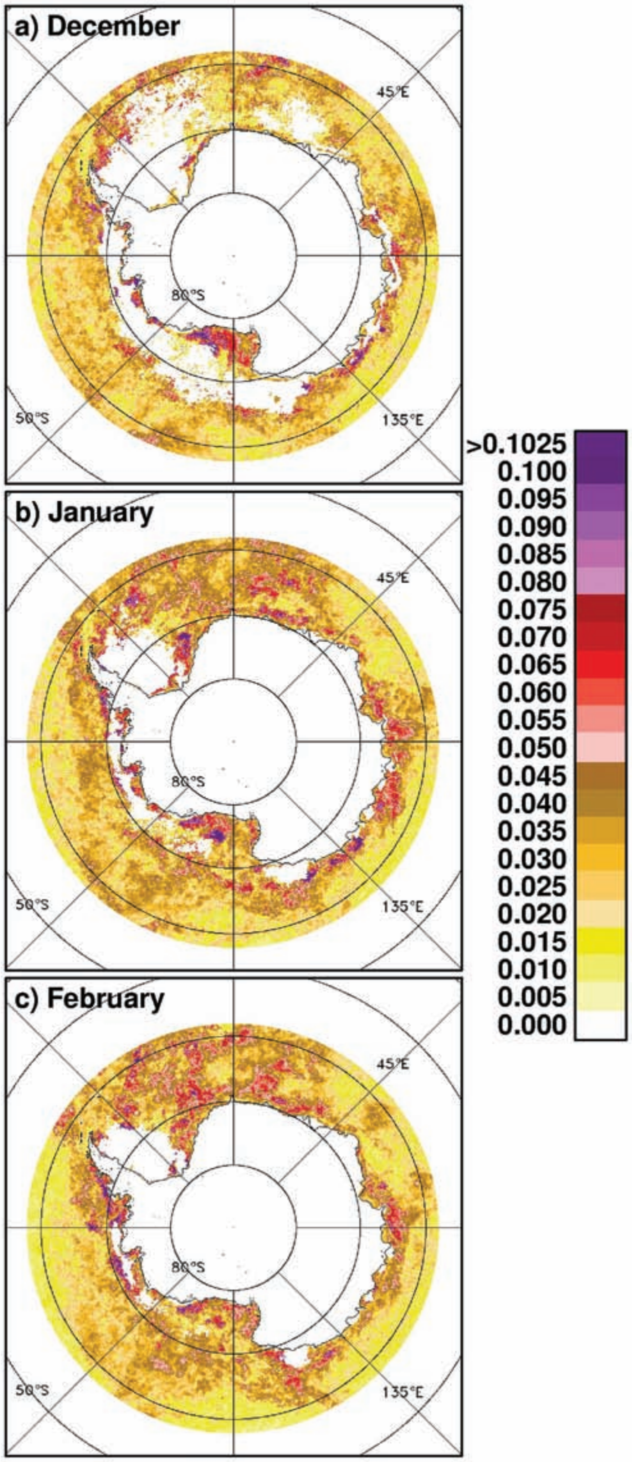

FIGURE 4. Standard deviations of the monthly productivity of the Southern Ocean for the years 1998–2006 for (a) December, (b) January, and (c) February. Black regions are those with fewer than five values; white areas have no data.

biomass accumulation (Sullivan et al., 1993; Arrigo and McLain, 1994). More refined treatments suggested that the Southern Ocean had a number of hot spots and short-lived increases in biomass (Moore et al., 1999) but, in large part, was extremely oligotrophic in nature.

For many years it was uncertain why the Antarctic was so oligotrophic. Many considered that vertical mixing created low-irradiance conditions, superimposed on the seasonal aspects of ice distributions and solar angle, both which restricted irradiance penetration into the surface (e.g., Smith and Nelson, 1985; Mitchell and Holm-Hansen, 1991). Macronutrients such as nitrate and phosphate were always in excess, and it was suggested that micronutrients such as iron or vitamin B-12 might limit production (e.g., Hart, 1934). However, reliable data on the concentrations of these micronutrients was lacking until the 1990s, when trace-metal clean measurements were made (e.g., Martin et al., 1990; Fitzwater et al., 2000). Iron concentrations were indeed found to be vanishingly small—in many cases less than 0.3 nM, even in coastal regions (Sedwick and DiTullio, 1997; Sedwick et al., 2000; Boyd and Abraham, 2001; Coale et al., 2003; de Baar et al., 2005). Furthermore, on the basis of laboratory studies and then field work, under low-irradiance conditions, iron demands increase; hence, the interactive effects between iron and light exacerbated the limitation, and this interaction was suggested to be of paramount importance in deeper, offshore regions (Boyd and Abraham, 2001; Smith and Comiso, 2008). Recently, it has been found that vitamin B-12 can limit or colimit phytoplankton growth in the Ross Sea (Bertrund et al., 2007), but the large-scale colimitation for the entire Southern Ocean remains to be demonstrated.

Other potential productivity-limiting factors have been addressed as well, such as grazing (Tagliabue and Arrigo, 2003) and temperature. However, herbivore biomass inventories are available only in selected regions and hence cannot be extrapolated over the entire Antarctic; furthermore, the effects of temperature have been considered to be of secondary importance in limiting growth and photosynthesis (Arrigo, 2007), although temperature may have a significant role in controlling assemblage composition.

It is useful to compare satellite means with other estimates that have been made, either via in situ measurements or numerical models. However, there are surprisingly few regions in the Southern Ocean that have adequate time series data to resolve the annual production signal; similarly, few regions have been the focus of intensive modeling. One region that has received assessments from both detailed measurements and numerical modeling is the

Ross Sea. Tremblay and Smith (2007, table 2) used the nutrient climatology compiled by Smith et al. (2003) and estimated the productivity by month and by year. The annual productivity based on nitrogen uptake was 155 g C m^{-1} y^{-1}, remarkably similar to the value estimated from our satellite model (Table 1). Smith and Gordon (1997) used measurements taken during November, along with other estimates, and calculated production to be 134 g C m^{-1} y^{-1}. Arrigo et al. (1998), using a numerical model, estimated productivity to be ~160 g C m^{-1} y^{-1}. The similarity between all of these estimates, either direct or indirect, and ours derived from satellite estimates and a vertically integrated production model is striking and gives us confidence that our procedure accurately assesses the production, despite the suggestion that chlorophyll retrievals from space in this area may contain significant errors (Arrigo et al., 1998). As the Ross Sea is the Antarctic's most spatial extensive phytoplankton bloom, the mean annual productivity is also near the maximum for the Antarctic. Our results suggest that the productivity of the Amundsen Sea may be slightly greater. The region is the site of a number of spring polynyas, and the optical properties of the water are likely similar to those in the Ross Sea. However, currently there are very limited in situ measurements available to confirm this substantial productivity.

It has been suggested that the high productivity of the Ross Sea is derived from substantial vertical stratification, early removal of ice, and adequate macro- and micronutrients for much of the growing season (Smith and Asper, 2001; Smith et al., 2003, 2006), coupled with limited grazing (Tagliabue and Arrigo, 2003). It has also been shown that during some summers a large "secondary" bloom occurs (Peloquin and Smith, 2007) and that these blooms occur approximately every three years. Peloquin and Smith (2007) suggested that summer iron limitation is occasionally reduced or eliminated by the intrusion of Modified Circumpolar Deep Water onto the continental shelf by oceanographic processes. Such a process would contribute greatly to the increased February variability we observed at some locations. A similar pattern of oceanic circulation has been suggested for the Prydz Bay/East Antarctica region as well (Smith et al., 1984), and it would be interesting to know if a similar influence of currents is responsible for the high productivity we observed in the Amundsen Sea.

TEMPORAL PATTERNS OF PRODUCTIVITY IN THE SOUTHERN OCEAN

The data that are used to derive the mean productivity shown in Figure 1 have also been analyzed for temporal trends (Figure 5). Mean Antarctic productivity for the past decade has shown a significant increase; furthermore, this increase is driven by changes that are largely confined to January and February (Smith and Comiso, 2008). Models have suggested that the productivity of the Southern Ocean will increase under atmospheric temperature increases driven by CO_2 loading (Sarmiento and Le Quéré, 1996; Sarmiento et al., 1998; Behrenfeld et al., 2006). The change will result from increased ice melting, which, in turn, should increase stratification, rather than a direct temperature effect. An increase in stratification would increase

TABLE 1. Summary of annual productivity estimates and method of computation for various portions of the Southern Ocean. "Southern" means the assessment was confined to regions south of 75°S.

Region	Annual productivity (g C m^{-2} y^{-1})	Method of estimation	Reference
Ross Sea	112	biomass accumulation	Nelson et al. (1996)
Ross Sea (southern)	190	biomass accumulation	Smith and Gordon (1997)
Southern Ocean	95.4–208	bio-optical model	Behrenfeld and Falkowski (1997a)
Southern Ocean	105	bio-optical model	Arrigo et al. (1998)
Ross Sea	57.6 ± 22.8	nutrient deficits	Sweeney et al. (2000)
Southern Ocean	62.4	bio-optical model	Moore and Abbott (2000)
Ross Sea	151 ± 21	bio-optical model	Arrigo and van Dijken (2003)
Ross Sea (southern)	145	numerical model	Arrigo et al. (2003)
Ross Sea	84–218	nutrient deficits	Smith et al. (2006)
Ross Sea (southern)	153	nutrient deficits	Tremblay and Smith (2007)
Ross Sea (southern)	54–65	bio-optical model	Smith and Comiso (2008)
Southern Ocean	20–150	bio-optical model	this study

the net irradiance environment available to phytoplankton and also decrease the magnitude of the iron-irradiance interaction, resulting in a decreased iron demand. Should iron inputs and concentrations remain the same, then the increased productivity would result in large-scale increases in phytoplankton growth and productivity. The observed change in the productivity estimated from satellites are not necessarily indicative of the changes predicted by the models and may reflect shorter-term trends that have altered current patterns, atmospheric inputs of iron, or other factors. It should also be noted that models do not include any colimitation effects of vitamin B-12, and if this effect were significant throughout the Southern Ocean, then the increase in productivity would be smaller than predicted. Regardless, the observed increase in annual productivity was unexpected, and the data analysis should be continued (using the same methods) as far into the future as possible to confirm this pattern.

Smith and Comiso (2008) also attempted to ascertain if the satellite data could be used to detect changes in productivity on a regional scale. Given that certain regions are having significant alterations in ice concentrations (e.g., the West Antarctic Peninsula–Amundsen/Bellingshausen Sea sector has had a >7% decrease per decade in ice concentration, while the Ross Sea sector has had an increase of >5%; Kwok and Comiso, 2002), it might be expected that changes in productivity are accompanying these changes. However, the temporal variability in the estimates of productivity of these areas was too great to allow for any trends to be determined, so at this time, it is impossible to determine if changes in higher trophic levels are occurring because of food web effects (via energetics) or by habitat modification (e.g., loss of reproductive sites and decreases in reproductive success).

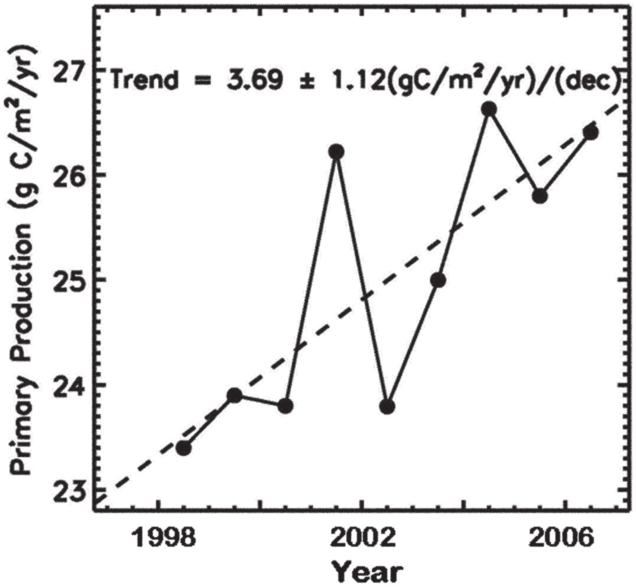

FIGURE 5. The temporal pattern of productivity for the entire Southern Ocean as derived from satellite data and a productivity model (from Smith and Comiso, 2008). The trend is derived from a linear regression of all points and is highly significant.

CONCLUSIONS

Tremendous advances have been made in our understanding of primary productivity in the Southern Ocean in the past 50 years. We have moved from an era of observational science into one that combines observations and experiments with large-scale assessments using data derived from multiple satellites and modeling using the same data. We recognize that the earlier assessments of productivity were biased by sampling and the nature of Antarctic productivity, and using unbiased techniques such as satellite data combined with robust models provides a means by which the temporal and spatial trends in phytoplankton production can be assessed. These methods have clearly demonstrated that the Southern Ocean as a whole is an oligotrophic area, with enhanced productivity on the continental shelves. Yet the shelf productivity is far from evenly distributed, and it is likely that oceanographic influences may play a large role in setting the maximum limits to production in the Southern Ocean.

It is suggested that the productivity of the entire Southern Ocean has increased significantly in the past decade, although the causes for such an increase remain obscure. Such changes have been predicted by numerical models, but it is far from certain that the observed changes are in fact related to climate change in the Antarctic. The short-term record also makes it difficult to interpret what the trend really means, especially in light of the possible effect of some climate modes like the Southern Hemisphere Annular Mode (Kwok and Comiso, 2002; Gordon et al., 2007). Only through extended analyses can such trends be confirmed and the causes for these changes ascertained. While increases in productivity of the magnitude shown may not induce major shifts in the ecology and biogeochemistry of the region, such changes, if they continue, may result in subtle and unpredicted impacts on the foods webs of the Antarctic ecosystem as well as changes in elemental dynamics. Knowledge of the environmental regulation of these changes in productivity is critical to the understanding of the ecology of the entire Southern Ocean and will provide insights into the potential changes that will undoubtedly occur in the coming years.

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